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ACOUSTIC WAVE PROPAGATION IN AN ADHESIVE BOND MODEL WITH DEGRADING INTERFACIAL LAYERS

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MATERIALS TESTING AND EVALUATION BRANCH

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ABSTRACT

This report discusses analytical and numerical approaches for the theoretical analysis of adhesively bonded structures having various bondline quality levels. Since the adhesive strength of an adhesively bonded structure is the critical failure problem of a bond under small loads, the discussions in this paper concentrate on mathematical models which use interfacial layers between the adherend and adhesive layers as a means to show various degrees of bond quality. The analytical method discussed is a reflection coefficient calculation for multi-layered structures in the frequency domain. The numerical approach used is the finite element method yielding time domain results for adhesively bonded structures having various interfacial layer conditions. Direct comparisons between the two methods are accomplished in the frequency domain, the time domain results obtained via the finite element method being appropriately Fast Fouier Transformed (FFT).

CONTENTS

INTRODUCTION

The strength of an adhesive bond depends both on its cohesive and adhesive properties. Cohesion is primarily a function of the type of adhesive, its mechanical properties, degree of cure, porosity, and thickness, all being properties of the adhesive bond's volume. Adhesion is dependent on the degree of molecular attraction and interaction between the adhesive and adherends, depending primarily on surface area conditions of the adhesive bond.[1]

In typical metal to metal adhesively bonded joints, surfaces are cleaned and primed prior to bonding. This process results in the formation of an interfacial layer typically only a fraction of a micrometer thick.[1] Improper surface preparation degrades the quality of this layer and ultimately causes adhesive bond failure.

Researchers[2-7,9,10] have tried to characterize adhesive bond properties using ultrasonic nondestructive evaluation time and frequency domain techniques. In most of the research, adhesively bonded structures were modeled as three-layered media; i.e., as adherend/adhesive/adherend models. Experimental measurements are made in the time domain, transformed into the frequency domain, and analyzed for changes in resonance minima: spacing, width, and depression depth. Others[8,11-16] have taken into account the interfacial layer and typically use obliquely incident ultrasonic wave methods for interrogation. In particular, Rose[8] has clearly shown that obliquely incident shear wave propagation aimed toward an interface can produce a significant increase in sensitivity in comparing good versus weak interface areas in an adhesively bonded structure.

In this paper, the effects of changing interfacial layer densities are examined to simulate various adhesive bond quality levels using normal incident longitudinal waves. Analytical and numerical methods, specifically finite elements, are used to examine the ultrasonic wave reflection coefficients and mechanical displacement responses, respectively, of an adhesively bonded structure consisting of adherends, interfacial layers, and an adhesive layer (five-layers). Differences in resonance minima location and spacing are correlated with interfacial layer parameters and suggest ways to estimate adhesive bond quality.

ANALYTICAL MODEL

Background

Brekhovskikh[17] showed three approaches for studying acoustic wave propagation. The possible approaches are: (1) by solving the wave equation with appropriate boundary conditions, (2) by means of an input impedance approach, analogous to transmission line theory, and (3) by considering the multiple reflections that occur at each interface of the modeled structure. The second approach is used in this paper for studying an adhesively bonded multi-layered structure.

At a plane boundary, a simple interface may exist between two different materials, having an acoustic plane wave incident upon and propagating from the upper to lower material with mechanical impedances of z_2 and z_1 for the upper and lower materials, respectively. The wave reflection coefficient may be obtained as follows:

$$r = \frac{z_1 - z_2}{z_1 + z_2} \quad (1)$$

where the mechanical impedance of any material is defined as the product of its material density and material acoustic wave velocity, $z = \rho v$.

Brekhovskikh shows that Equation 1 may be rewritten in the form,

$$r = \frac{z_{in} - z_2}{z_{in} + z_2} \tag{2}$$

where z_{in} equals z_1 of Equation 1 and is defined as the impedance of the reflecting medium. This leads to the general equations for calculating the input impedance and reflection coefficient that can then be used successively for modeling multi-layered systems.

The geometry for plane wave propagation in multi-layered systems is illustrated in Figure 1 where normal acoustic plane incidence is assumed here. Both the top and bottom media are semi-infinite in length with an acoustic plane wave incident on the top boundary. The top media is numbered n+1, the bottom media is number 1, and there are n-2 intermediate layers numbered 2,3,4,...,n.

For the n^{th} layer the input impedance is:

$$z_{in}^{(n)} = \left(\frac{z_{in}^{(n-1)} - i z_n \tan\phi_n}{z_n - i z_{in}^{(n-1)} \tan\phi_n} \right) z_n \tag{3}$$

where for normal incidence $\phi_n = k_n d_n$, $k_n = 2\pi f/v_n$, k_n is the wave number, d_n is thickness, f is frequency, and v_n is the wave velocity.

The reflection coefficient for the n^{th} layer is:

$$r = \frac{z_{in}^{(n)} - z_{n+1}}{z_{in}^{(n)} + z_{n+1}} \tag{4}$$

which has the same form as Equation 1, the reflection coefficient for a one boundary situation.

Model Description

A typical adhesively bonded structure consists of two adherends, two interfacial layers on each side of the adhesive layer, and the adhesive layer itself. Aluminum is the adherend material for this case. Generally, aluminum oxide and primer layers are generated in the anodization and priming processes to enhance bond quality.[12] Adherends can be considered as finite thickness layers, or when short ultrasonic pulses are used, as semi-infinite spaces. Since a very short pulse excitation is considered in the application presented, comparisons may be justifiably accomplished between both these adherend situations. The aluminum oxide and primer materials are modeled as one interface layer both above and below the adhesive material due to the very small thickness dimensions of these individual components.

For the purposes of the analytical reflection coefficient model, the upper and lower media are considered to be semi-infinite in length while the interfacial and adhesive layers are finite in thickness. The adhesive bond and interfacial layers are shown geometrically in Figure 2. There are five regions; three are intermediate layers d_2, d_3, and d_4 which represent the interfacial layer above the adhesive, the adhesive, and the interfacial layer below the adhesive, respectively.

The input impedance for this five-layer system is $z_{in}(4)$, obtained through successive applications of Equation 3, being recursively substituted in Equation 4 yielding the reflection coefficient of the layered system as follows:

$$r = \frac{z_{in}^{(4)} - z_5}{z_{in}^{(4)} + z_5} \tag{5}$$

where z_5 is the mechanical impedance of the 5^{th} material.

This reflection coefficient, Equation 5, is used to examine the effects of a degrading adhesive bond for two specific cases. A perfect bond is defined with the interfacial layer having either the same mechanical impedance, acoustic wave velocity, and material density as the adherend for Case 1, or as the adhesive for Case 2. Degrading interfacial layer conditions are modeled by varying the mechanical impedance of the interfacial layers through decreases in the material density of the layer. The various conditions for Cases 1 and 2 are listed in Tables 1 and 2, respectively.

NUMERICAL MODEL: FINITE ELEMENT APPROACH

The analytical model previously described is valid for one-dimensional wave propagation analysis and for situations where the effects of the second and third dimensions have a very small consequence on the mechanical displacement solution of the acoustic wave equation. The acoustic wave equation for damped media is given as follows:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = V_L \frac{\partial^2 \mathbf{u}}{\partial z^2} + V_s \frac{\partial^2 \mathbf{u}}{\partial y^2} + \eta_L \frac{\partial^3 \mathbf{u}}{\partial z^2 \partial t} + \eta_S \frac{\partial^3 \mathbf{u}}{\partial y^2 \partial t} + F(t) \tag{6}$$

where ρ is the material density in kg/m^3, V_L is the longitudinal phase velocity in m/sec, V_s is the shear phase velocity in m/sec, η_L is the mechanical damping parameter in N·s/m^2 in the z-direction, η_s is the mechanical damping parameter in N·s/m^2 in the y-direction, and F(t) is the applied force density in N/m^2 on the structural surface as a function of time.

The finite element method transforms the differential equation given by Equation 6 into an integral relationship and, finally, into an algebraic system of equations which may be solved on a digital computer. Details of this procedure will not be given here but may be found in References 18 through 20. A two-dimensional finite element analysis is given on the adhesively bonded structure for two cases: (1) A spatially uniform force application of finite aperture width applied by a transducer (transducer not modeled) into an adhesively bonded structure at a center frequency of 15 MHz where the interfacial layer has a material

density proportional to the aluminum adherend (same as percent of bond quality), and (2) same as Case 1 except that force excitation is at 10 MHz and the interfacial layer has a material density proportional to that of the adhesive material (percent of bond quality). The forcing function is the temporal raised cosine function as follows:

$$F(t) = [1 - \cos\left(\frac{2\pi f_0 t}{3}\right)]\cos(2\pi f_0 t) \qquad 0 \le t \le \frac{3}{f_0} \tag{7}$$

where f_0 is the transducer's center operating frequency, F(t) is the time domain raised cosine force density input with uniform surface application to the structure.

The idea of using the finite element method is that it solves any field variable of interest at discrete nodal locations throughout a domain; in this case for an adhesively bonded structure. Mechanical displacements are solved in this case using this method for the five-layered structure shown in Figure 3.

The choice of both the finite element spatial discretization level and the chosen time step increment for simulating the mechanical displacement solution must be done appropriately in order to ensure valid solution computations. For the purposes of the spatial discretization, a spatial sampling of 8 nodal points per center frequency wavelength is chosen. By the Nyquist criterion, a minimum of two samples per wavelength is required to represent any signal.[21] Since harmonics of the fundamental frequency exist in the mechanical displacement response, it is felt that Nyquist spatial sampling up to the fourth harmonic is sufficient for practical purposes; i.e., this being the principal reason that the 8-node per fundamental frequency wavelength sampling requirement is chosen.

Since the time domain formulation is an explicit time stepping scheme,[18] the time step size used is dependent on the spatial discretization; in this case the 8-node per wavelength criterion. The matrix equation formulation of Equation 6 prior to time discretization is given by:

$$[M]\{\ddot{\mathbf{u}}\} + [D]\{\dot{\mathbf{u}}\} + [K]\{\mathbf{u}\} = \{F\} \tag{8}$$

where [M] is called the mass matrix, [D] is the mechanical damping matrix, [K] is the mechanical stiffness matrix, and $\{\mathbf{u}\}$ is the mechanical displacement vector with its associated derivatives.[18,20]

The finite difference time discretization of the second and first derivatives of mechanical displacement is accomplished by Equations 9 and 10:

Central Difference Approximation:

$$\ddot{\mathbf{u}}_t \cong \frac{1}{\Delta t^2}\,[\mathbf{u}_{t+\Delta t} - 2\,\mathbf{u}_t + \mathbf{u}_{t-\Delta t}] \tag{9}$$

where $\ddot{\mathbf{u}}_t$ is the central difference approximation for the second time derivative of $\mathbf{u}$, t is the time step size, and $\mathbf{u}_{t+\Delta t}$, $\mathbf{u}_t$, and $\mathbf{u}_{t-\Delta t}$ are nodal values of mechanical displacements at the three consecutive time instants, $t+\Delta t$, t, and $t-\Delta t$.

Backward Difference Approximation:

$$\dot{\mathbf{u}}_t \cong \frac{1}{\Delta t}\left[\mathbf{u}_t - \mathbf{u}_{t-\Delta t}\right] \tag{10}$$

where $\dot{\mathbf{u}}_t$ approximates the first time derivative of $\mathbf{u}$ at time t.

The final algorithm, given by Equation 11, used for the mechanical displacement calculations combining finite elements in the spatial domain and finite differences in the time domain is given by:

$$\mathbf{u}_{t+\Delta t} \cong \frac{\Delta t}{M_{ii}}\{\Delta t(\mathbf{F}_t - [K]\,\mathbf{u}_t) + [D](\mathbf{u}_t - \mathbf{u}_{t-\Delta t})\} + 2\mathbf{u}_t - \mathbf{u}_{t-\Delta t} \tag{11}$$

where M_{ii} is the diagonalized mass matrix.[18]

Using Fourier Stability Analysis,[22] the stability relationships between the spatial and temporal discretization levels may be derived. For the undamped acoustic wave propagation problem, the final stability relationship for the undamped case is:

$$\Delta t \le \frac{\Delta y \, \Delta z}{V_{max}\sqrt{\Delta y^2 + \Delta z^2}} \tag{12}$$

where Δt is the time step, Δy is the spatial discretization in the y-direction, Δz is the spatial discretization in the z-direction, and V_{max} is the maximum phase velocity in the structure.

Tables 3 and 4 give all of the information on the resulting mesh discretization levels including the required spatial and time step requirements for stable algorithms for Cases (1) and (2) previously described.

For Case 1, where a transducer center frequency of 15 MHz was used, and the adhesive interface was initially modeled like aluminum, the required time step size was 1.060 nanoseconds and the actual time step used was 1.000 nanosecond.

For Case 2, where a transducer center frequency of 10 MHz was used, and the adhesive interface was initially modeled like the adhesive, the required time step size was 3.280 nanoseconds and the actual time step used was 1.000 nanosecond.

Since the adhesively bonded structure is rectangular in shape and the force excitation is applied along the center of the top layer, the condition of symmetry may be advantageously applied. Only one-half of the structure needs to be modeled, either the right or left half, by assuming a zero displacement condition in the y-direction along the symmetry axis (z-direction). This condition is shown in Figure 4 using the right half version of the model.

NUMERICAL AND ANALYTICAL RESULTS DISCUSSION

Numerical results calculated via the finite element method are time domain results which are found at every discrete time step for the time interval simulation desired at all the nodal locations in the given domain modeled; in this case the adhesively bonded structure. One observation node is chosen at the top center node of the physical structure, or equivalently, the upper left node of the symmetric model for the finite element simulation (Figure 4). The time and frequency domain results presented are based on this particular nodal location.

The comparisons between the analytical and numerical results are done totally in the frequency domain. All time domain results obtained for the observation node are shown for the time interval of the first echo pulse only since this timeframe gives the pertinent information about the bondline. These results are then Fast Fourier Transformed (FFT) into the frequency domain. The overall frequency range is studied for the case of a 100% quality level bond for Cases 1 and 2. For Case 1, the effective bondline thickness is 70 microns, and a resonant frequency (amplitude minimum) at 15 MHz is detected analytically. For Case 2, the effective bondline thickness is 84 microns, and a resonant frequency (amplitude minimum) at 12.5 MHz is detected analytically. These minima correspond exactly to the one-dimensional analyses for bondlines with such thickness dimensions. Both the reflection coefficient results and the displacement output frequency responses show these distinct minima very clearly in Figures 5 and 7 (for the 100% quality level simulation) for Case 1, and Figures 10 and 11 (for the 100% quality level simulation) for Case 2.

The real advantage of using a numerical method is in its ability to solve problems where analytical methods are not possible. It is always necessary, however, to compare with problems which can be solved analytically in order to gain confidence in the chosen numerical model. It is for this reason that the case of a good bond (a 100% quality bond) excited with a normal incidence pulse is performed and its results are shown initially. FFTs are performed on the numerical time domain results shown in Figures 8 and 12 and the corresponding frequency domain results of the analytical and numerical results are appropriately overlayed in Figure 14. There is an excellent comparison for Cases 1 and 2 between the numerical and analytical analyses, especially in the vicinity of frequency minima locations. The comparisons for the overall frequency range, however, are not one-to-one although they are good. This is attributed to several reasons. The finite element method employed for the numerical approximation here is a two-dimensional versus a one-dimensional model. Additionally, mode coupling exists between the longitudinal and shear responses of the adhesively bonded structure. This is true although the present structure is driven with a force distribution only in the longitudinal direction. This mode coupling is accounted for in the different magnitude values of the frequency spectra of the output responses of the analytical versus numerical results. It is noteworthy to observe that the frequency values of the numerical results are consistently higher than the analytical ones. This is characteristic of a finite element formulation using an explicit time stepping scheme based on the central difference operator.[18]

The adhesively bonded structures with partially good quality bondlines are investigated for 10%, 20%, and 50% bond quality levels. The finite element time domain results are shown in Figures 8 and 12, transformed into the frequency domain in Figures 9 and 13, and comparisons are made for the minima frequency results between the analytical reflection coefficient (Figure 6) and numerical results for Cases 1 and 2. These minima results are shown for the different levels of bond quality in Table 5. Note that the error between the frequency minima is always less than about 2% demonstrating that the numerical approach is certainly a

credible approach for analyzing adhesively bonded structures with bondlines of variable quality levels. Additionally, a correlation may be reached by inspecting the widths of frequency spectra in the vicinity of the amplitude minima locations. These widths or "bandwidths" appear to be somewhat proportional in size to the quality of the adhesive bondline being analyzed; i.e., being widest for the higher quality bonds. This was consistently found not only in the comparisons between numerical and analytical results presented here but also in a theoretical and experimental development made by Chang.[23] This showed that spectral depression bandwidths may be indicators of bond strength as well as being related to the acoustic interfaces of a bonded joint.[7]

CONCLUSIONS

This paper demonstrates that the finite element method is a feasible means of evaluating adhesively-bonded structures where the quality of the bondline enters directly into the analysis. Since adhesive failures occur with a higher probability than cohesive failures, an interfacial layer was introduced to simulate weak bondline conditions in the modeled structure. The comparison of numerical versus analytical methods shows that the detection of frequency minima by numerical methods for the five-layered model simulated for various bond quality levels indeed gives very similar resonant frequency results to analytical methods. Additionally, the usage of interfacial layers as a means to simulate weak conditions at a bondline surface area junction appears to be an excellent way to model the adhesive failure conditions usually encountered. Characteristics which occur in the frequency domain for various quality bondline conditions verified by the finite element model are: (1) a reduction in the resonant frequency location for reduced bondline quality level, (2) a reduction in the bandwidth around the frequency minima location for reduced bondline quality level, (3) excellent comparisons with analytical reflection coefficient model (two-dimensional versus one-dimensional analyses), and (4) verification of the interfacial layer since it is qualitatively consistent with the theoretical and experimental discussion given by Chang.[23]

Table 1. CASE 1 - ANALYTICAL PARAMETER LIST

	Velocity (v) (m/s)	Density (ρ) (kg/m^3)	Impedance (z) (x10^6 kg/m^2 sec)	Thickness (d) (m)
Adherend	6370	2710	17.25	Semi-infinite
Adhesive	2100	1120	2.35	70.0×10^{-6}
Interface Layers:*				
Model-a 100%	6370	2710	17.25	7.0×10^{-6}
Model-b 50%	6370	1360	8.66	7.0×10^{-6}
Model-c 20%	6370	540	3.44	7.0×10^{-6}
Model-d 10%	6370	270	1.72	7.0×10^{-6}

*Percentage of adherend density corresponding impedance calculated using $z = \rho v$

Table 2. CASE 2 - ANALYTICAL PARAMETER LIST

	Velocity (v) (m/s)	Density (ρ) (kg/m^3)	Impedance (z) (x10^6 kg/m^2 sec)	Thickness (d) (m)
Adherend	6370	2710	17.25	Semi-infinite
Adhesive	2100	1120	2.35	70.0×10^{-6}
Interface Layers:*				
Model-a 100%	2100	1120	2.35	7.0×10^{-6}
Model-b 50%	2100	560	1.18	7.0×10^{-6}
Model-c 20%	2100	220	0.47	7.0×10^{-6}
Model-d 10%	2100	110	0.23	7.0×10^{-6}

*Percentage of adhesive density, corresponding impedance calculated using $z = \rho v$

Table 3. CASE 1 - NUMERICAL PARAMETER LIST

Thickness (m)	V_L (m/s)	V_S (m/s)	#Z Elements	$\lambda_L/8$ (m)	$\lambda_S/8$ (m)	Δt (nsec)	ΔZ (m)	$\Delta Y/\Delta Z$
3.17×10^{-3}	6370	3110	123	5.3×10^{-5}	2.59×10^{-5}	2.861	2.58×10^{-5}	0.998
7.00×10^{-6}	6370	3110	1	5.3×10^{-5}	2.59×10^{-5}	1.060	7.00×10^{-6}	3.68
7.00×10^{-5}	2100	1050	9	1.75×10^{-5}	8.75×10^{-6}	3.542	7.77×10^{-6}	3.31
7.00×10^{-6}	6370	3110	1	5.3×10^{-5}	2.59×10^{-5}	1.060	7.00×10^{-6}	3.68
4.77×10^{-3}	6370	3110	185	5.3×10^{-5}	2.59×10^{-5}	2.861	2.58×10^{-5}	0.998

#DOF = 316160 nz = 320 ny = 494 Δt = 1.060 nsec

Table 4. CASE 2 - NUMERICAL PARAMETER LIST

Thickness (m)	V_L (m/s)	V_S (m/s)	#Z Elements	$\lambda_L/8$ (m)	$\lambda_S/8$ (m)	$\Delta\tau$ (nsec)	ΔZ (m)	$\Delta Y/\Delta Z$
3.17×10^{-3}	6370	3110	82	7.96×10^{-5}	3.88×10^{-5}	4.296	3.87×10^{-5}	1.000
7.00×10^{-6}	2100	1050	1	2.625×10^{-5}	1.313×10^{-5}	3.280	7.00×10^{-6}	5.531
7.00×10^{-5}	2100	1050	6	2.625×10^{-5}	1.313×10^{-6}	5.316	1.166×10^{-6}	3.319
7.00×10^{-6}	2100	1050	1	2.625×10^{-5}	1.313×10^{-5}	3.280	7.00×10^{-6}	5.531
4.77×10^{-3}	6370	3110	123	7.96×10^{-5}	3.88×10^{-5}	4.304	3.882×10^{-5}	0.9974

#DOF = 140812 nz = 241 ny = 329 Δt = 3.280 nsec

Table 5. FREQUENCY MINIMA COMPARISON

Case/Model		Density of Interface Layers (kg/m^3)	Frequency Minima Locations: Analytical (MHz)	Numerical (MHz)
Case 1	Model-a	2710	15.00	14.93
	Model-b	1360	14.80	14.73
	Model-c	540	14.35	14.31
	Model-d	270	13.75	13.72
Case 2	Model-a	1120	12.50	12.40
	Model-b	560	10.80	10.80
	Model-c	220	8.20	8.12
	Model-d	110	6.20	6.16

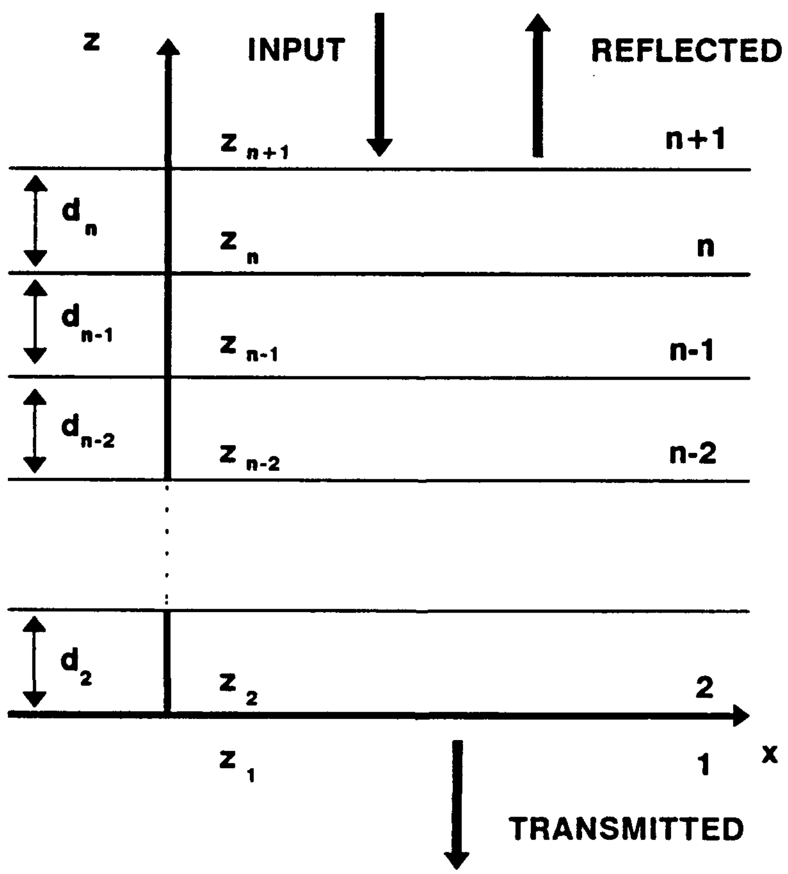


Figure 1. Multi-layered structure model used for calculation of reflection coefficient.

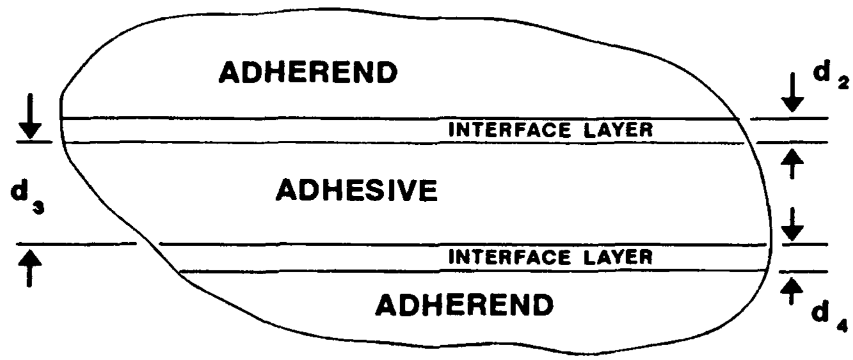
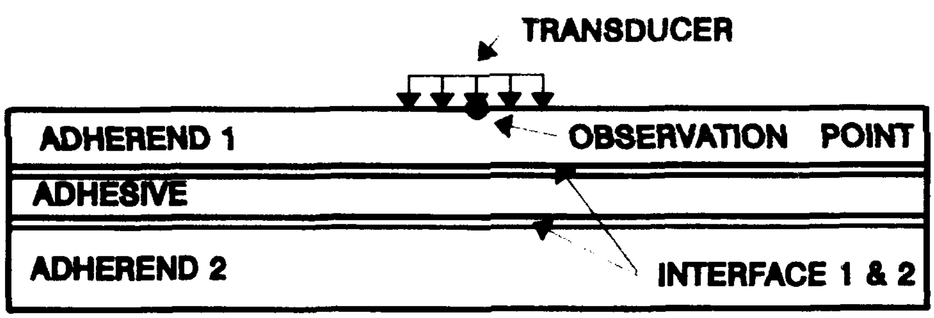


Figure 2. Analytical representation of adhesively bonded structure.



LAYER	THICKNESS
ADHEREND 1	3175 μm
INTERFACE 1	7 μm
ADHESIVE	70 μm
INTERFACE 2	7 μm
ADHEREND 2	4775 μm

Figure 3. Adhesively bonded structure geometry with finite aperture transducer pulsed excitation (adherends are aluminum).

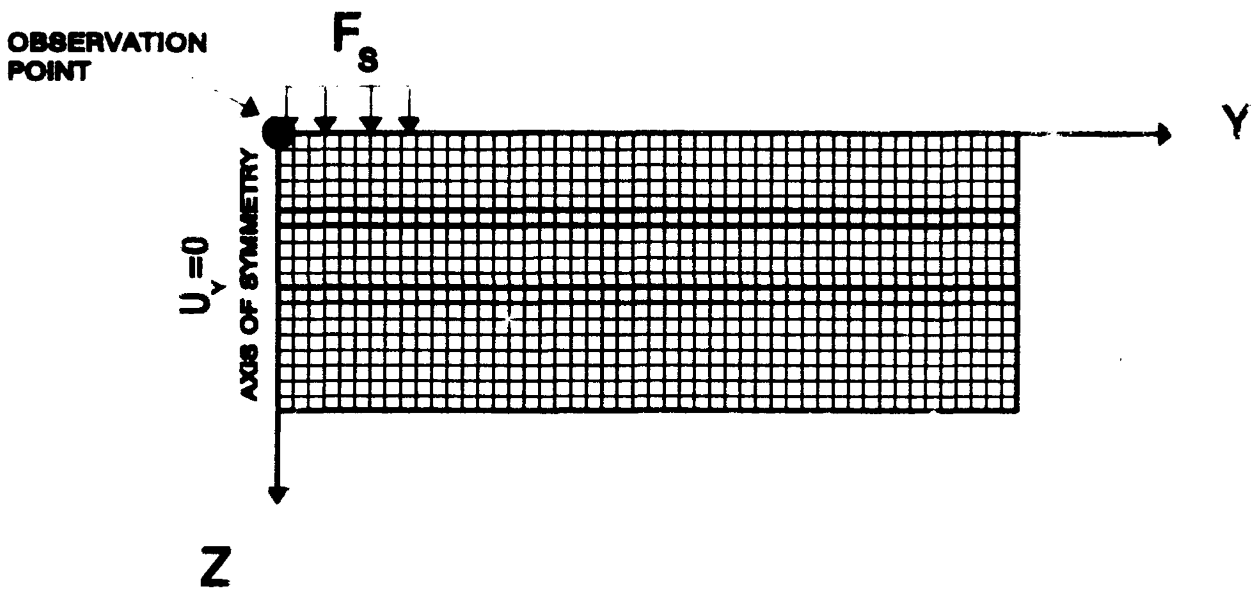


Figure 4. Possible finite element mesh of five-layered structure exploiting mechanical symmetry, shear displacements set to zero-value on symmetry axis.

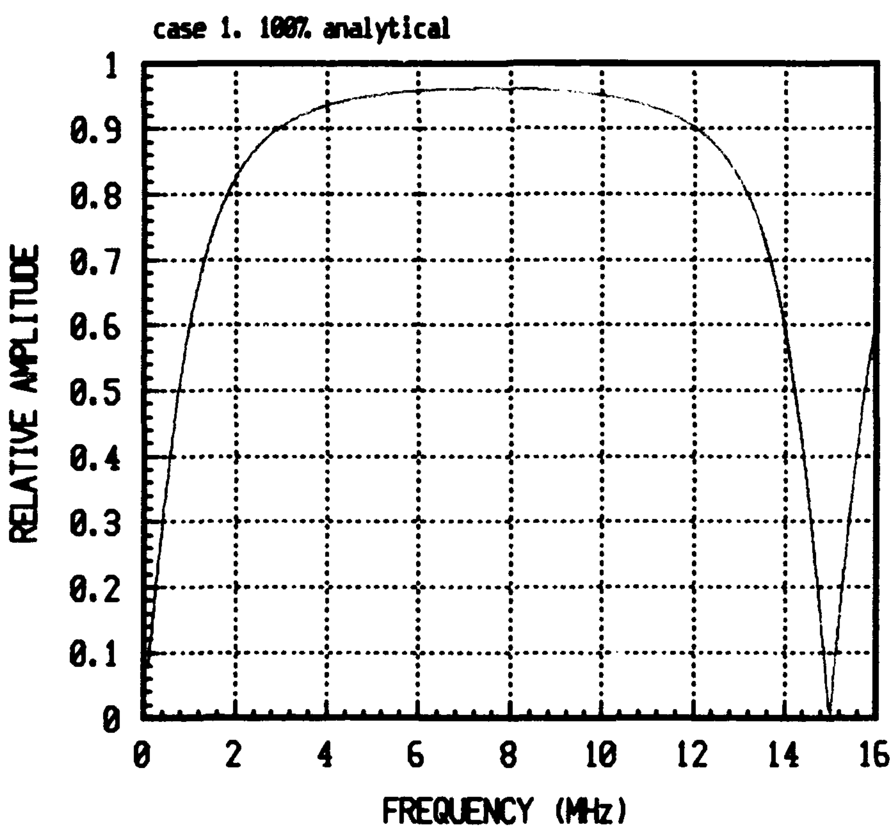


Figure 5. Analytical reflection coefficient Case 1 (good bond)

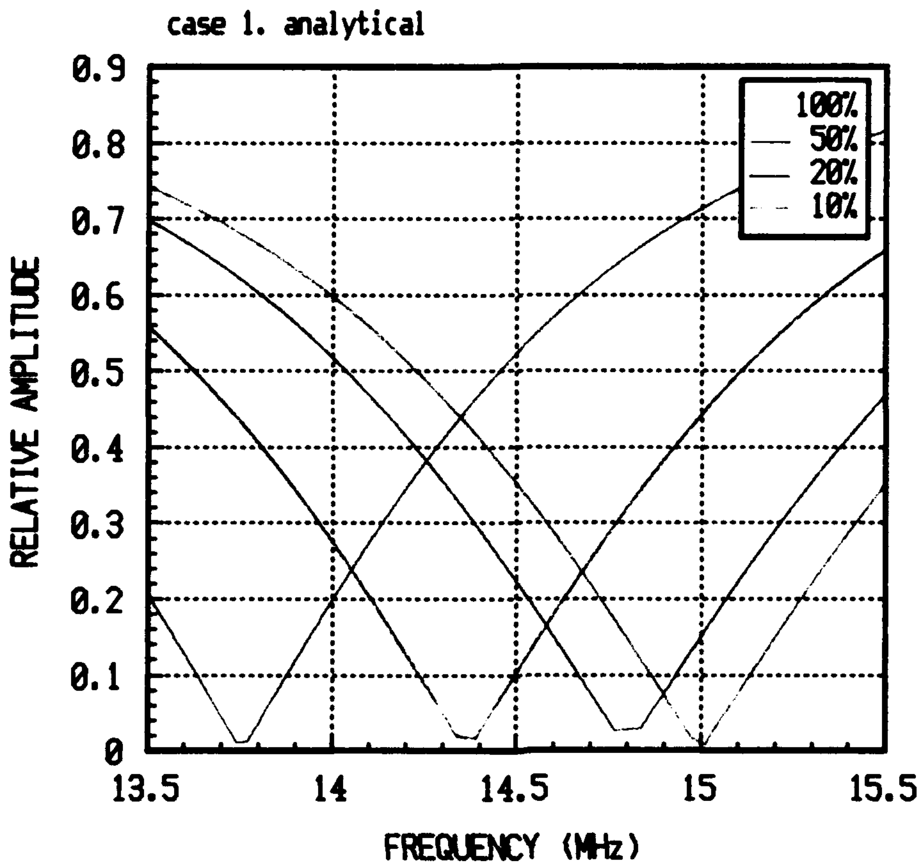


Figure 6. Analytical reflection coefficients for Case 1. Bond quality levels: 10%, 20%, 50%, 100% - 13.5 ≤ f ≤ 15.5 MHz.

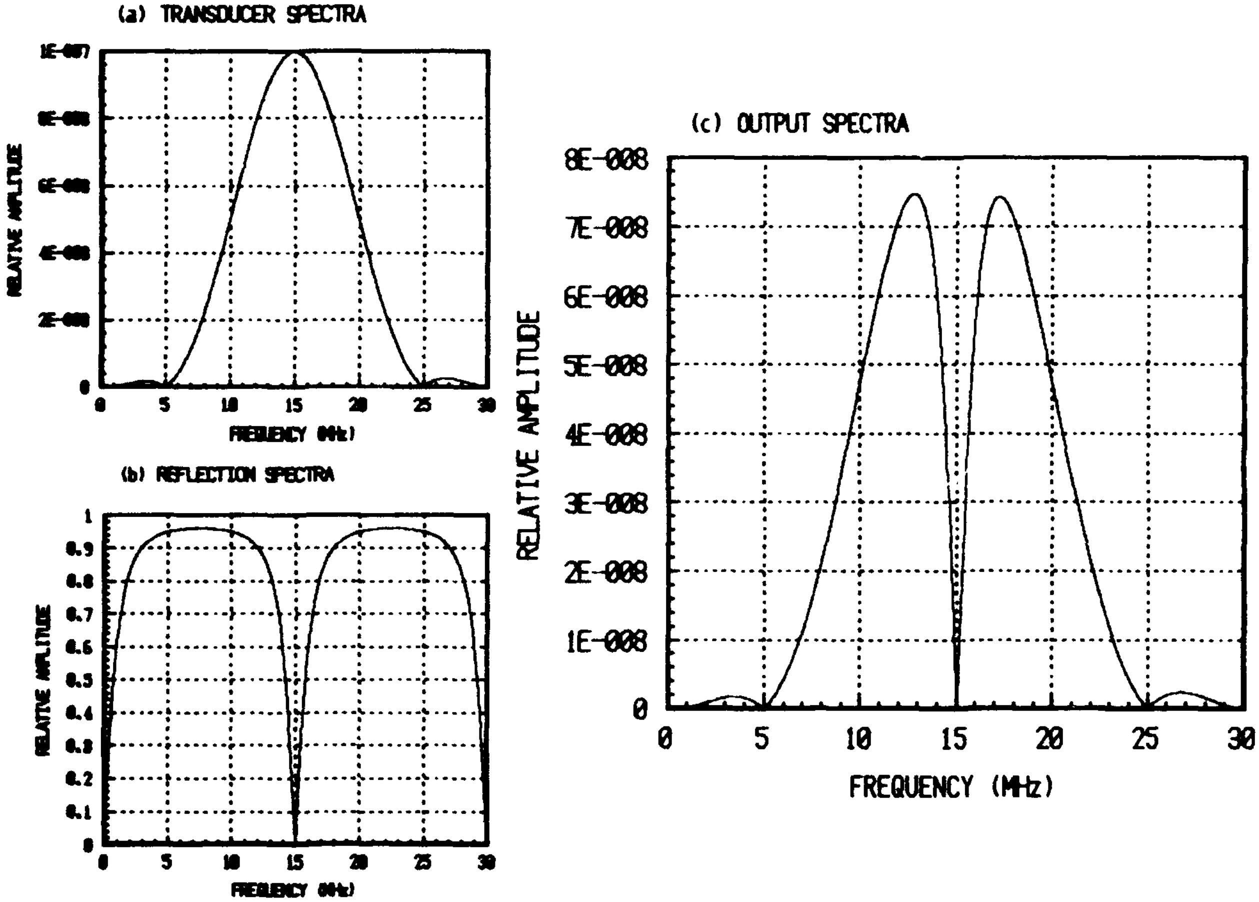


Figure 7. Analytical frequency domain analysis for good bond (100%), Case 1: (a) Fourier transform of raised cosine with f_0 = 15 MHz, (b) Reflection coefficient of adhesively bonded model, and (c) Relative amplitude of transformed mechanical displacement response.

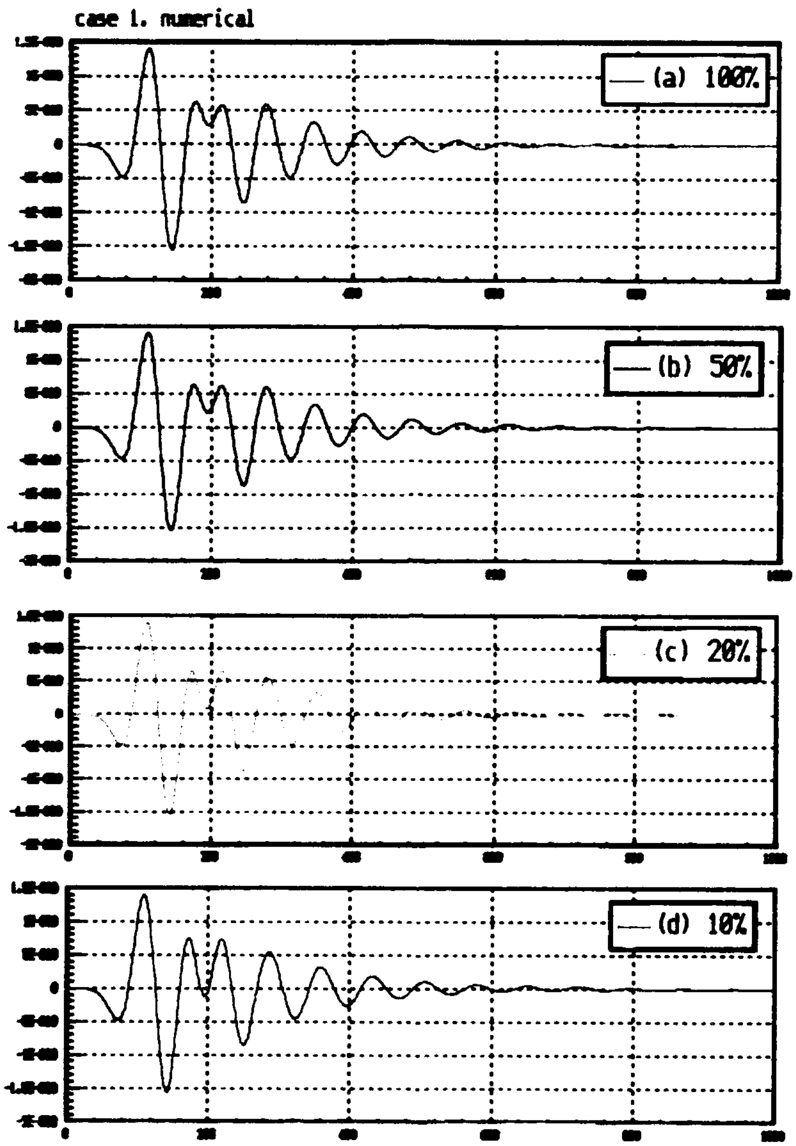


Figure 8. Time domain mechanical displacement responses, Case 1: (a) 100% bond quality level, (b) 50% bond quality level, (c) 20% bond quality level, and (d) 10% bond quality level.

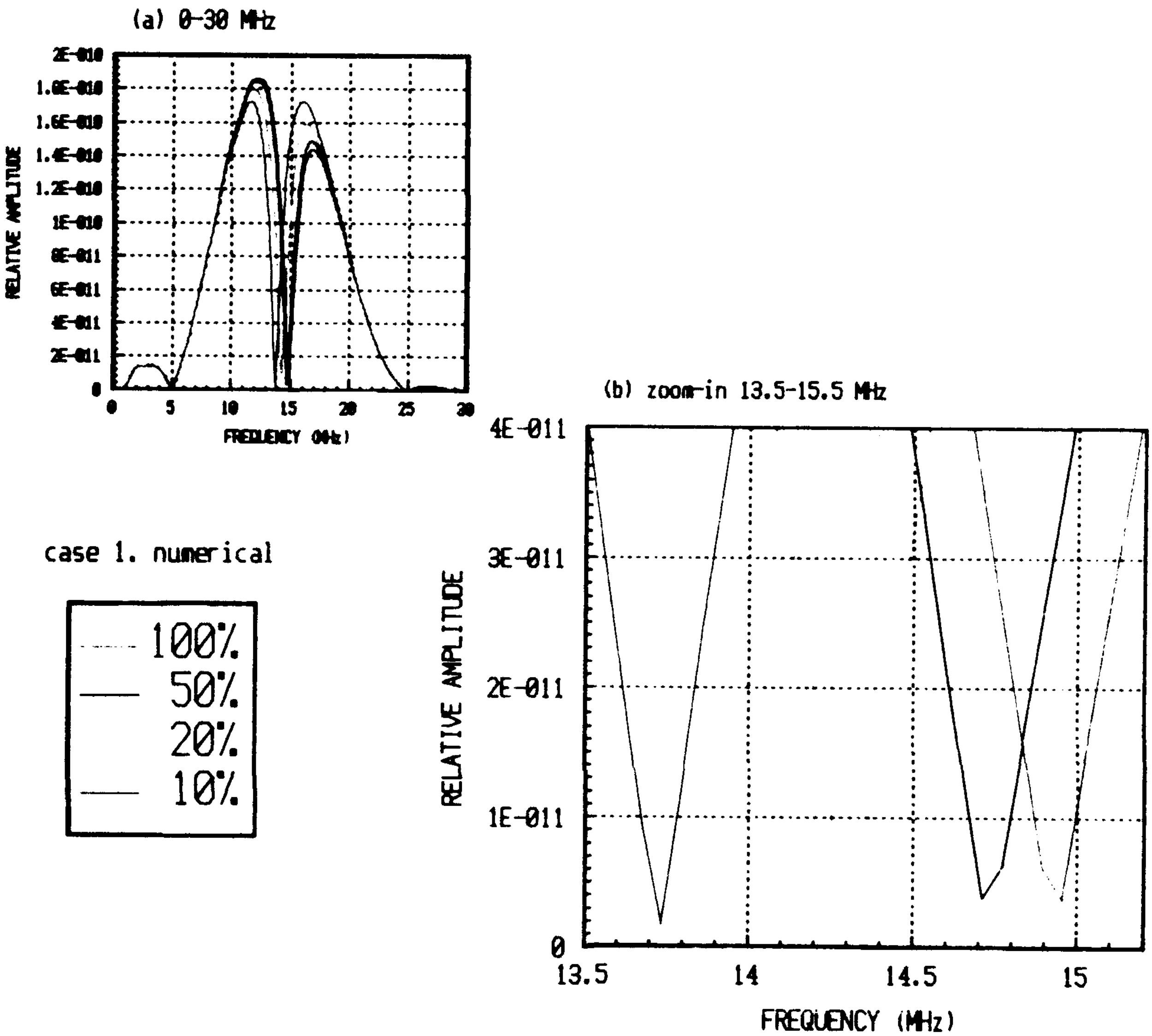


Figure 9. Frequency domain mechanical displacement responses, Case 1: (a) Responses for frequency range 0 ≤ f ≤ 30 MHz, and (b) Responses for frequency range 13.5 ≤ f ≤ 15 MHz.

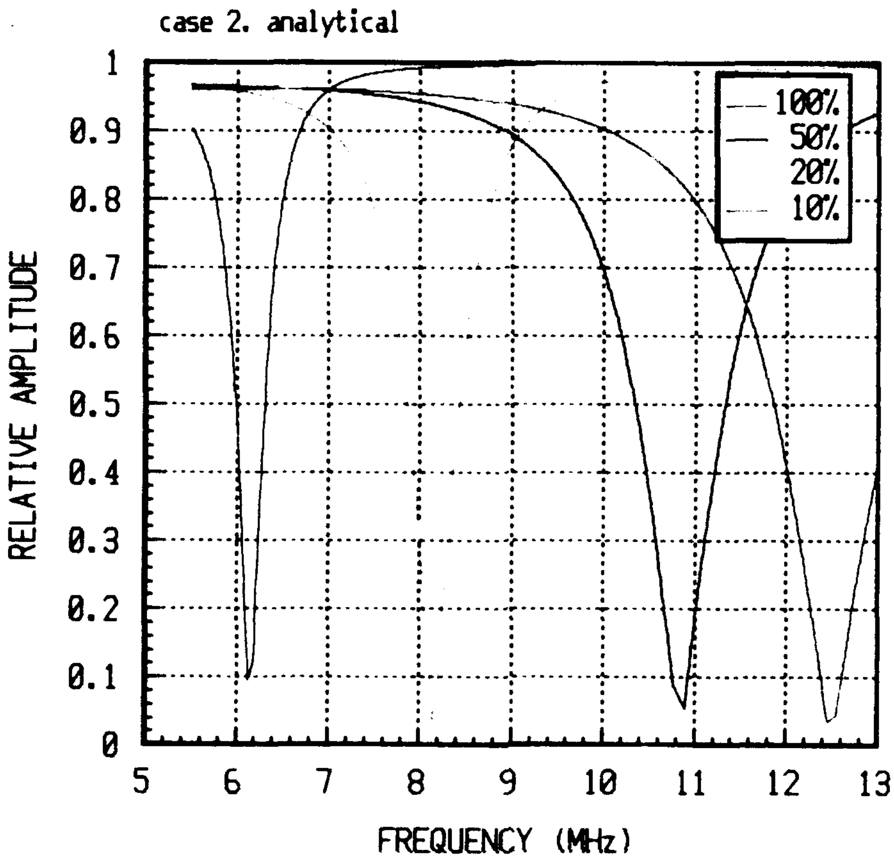


Figure 10. Analytical reflection coefficients Case 2, $5 \leq f \leq 13$ MHz for 10%, 20%, 50%, and 100% bond quality levels.

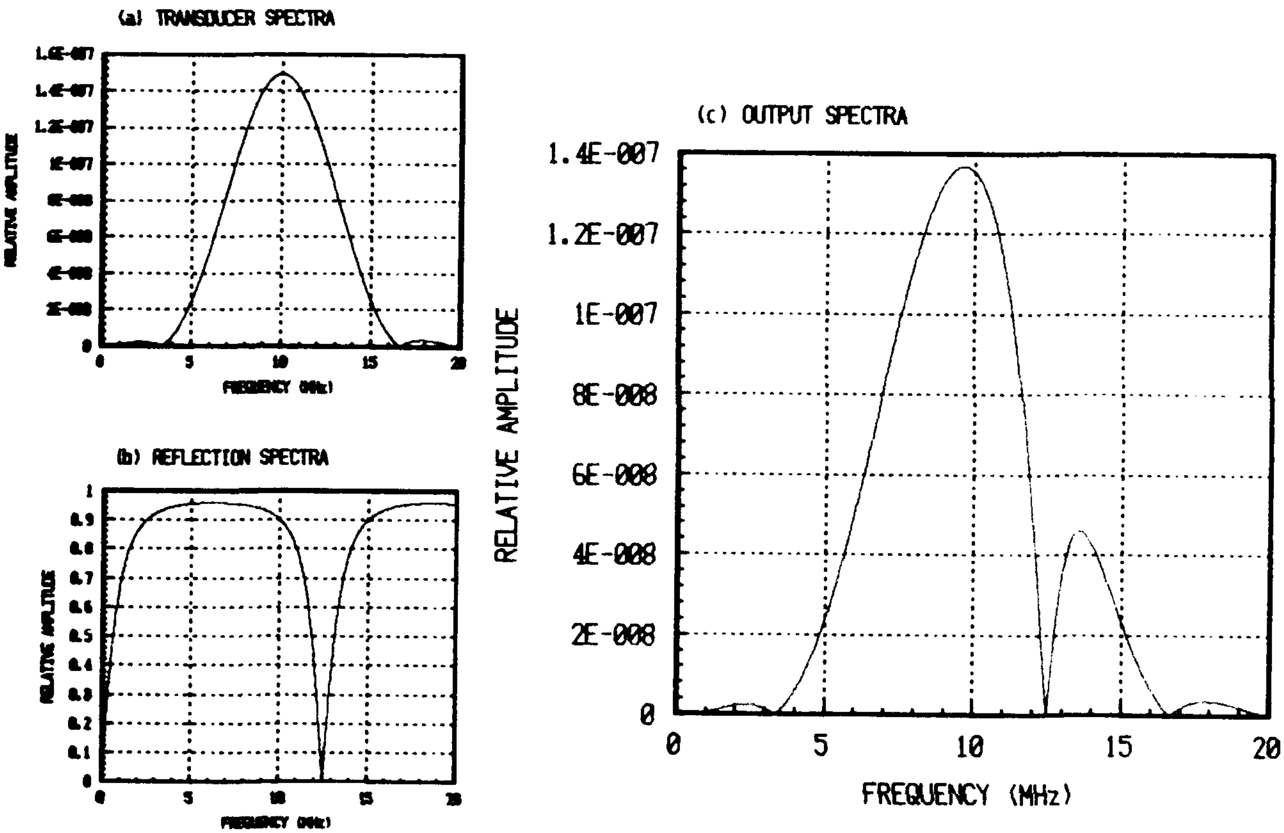


Figure 11. Analytical frequency domain responses for good bond Case 2: (a) Fourier transform of raised cosine with f_0 = 10 MHz, (b) Reflection coefficient of adhesively bonded model, and (c) Relative amplitude of transformed mechanical displacement response.

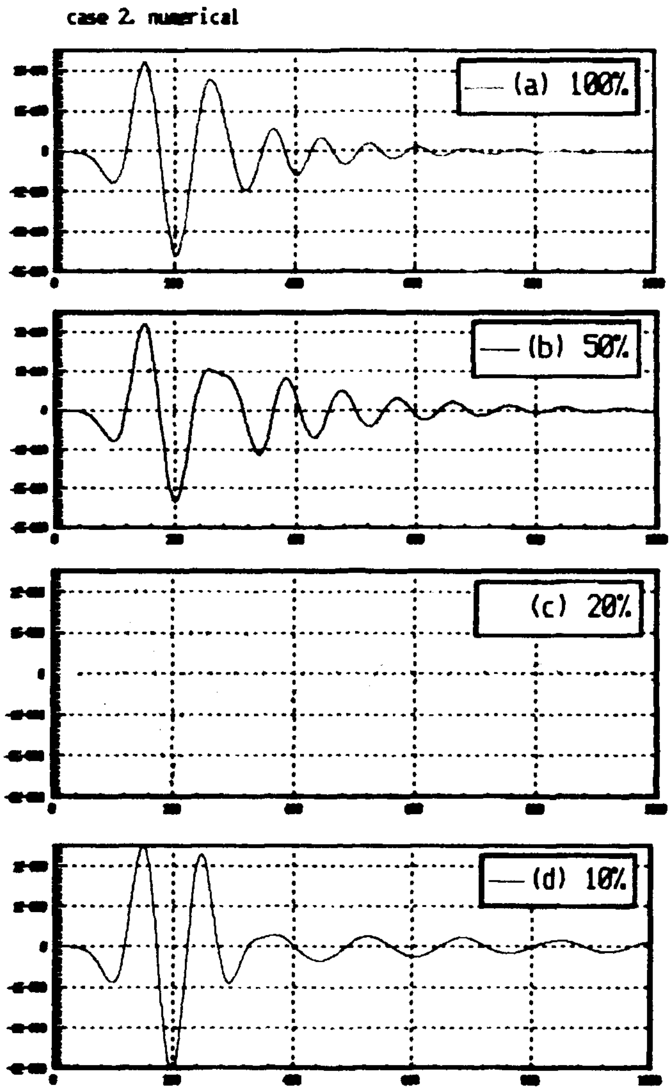


Figure 12. Time domain mechanical displacement responses, Case 2: (a) 100% bond quality level, (b) 50% bond quality level, (c) 20% bond quality level, and (d) 10% bond quality level.

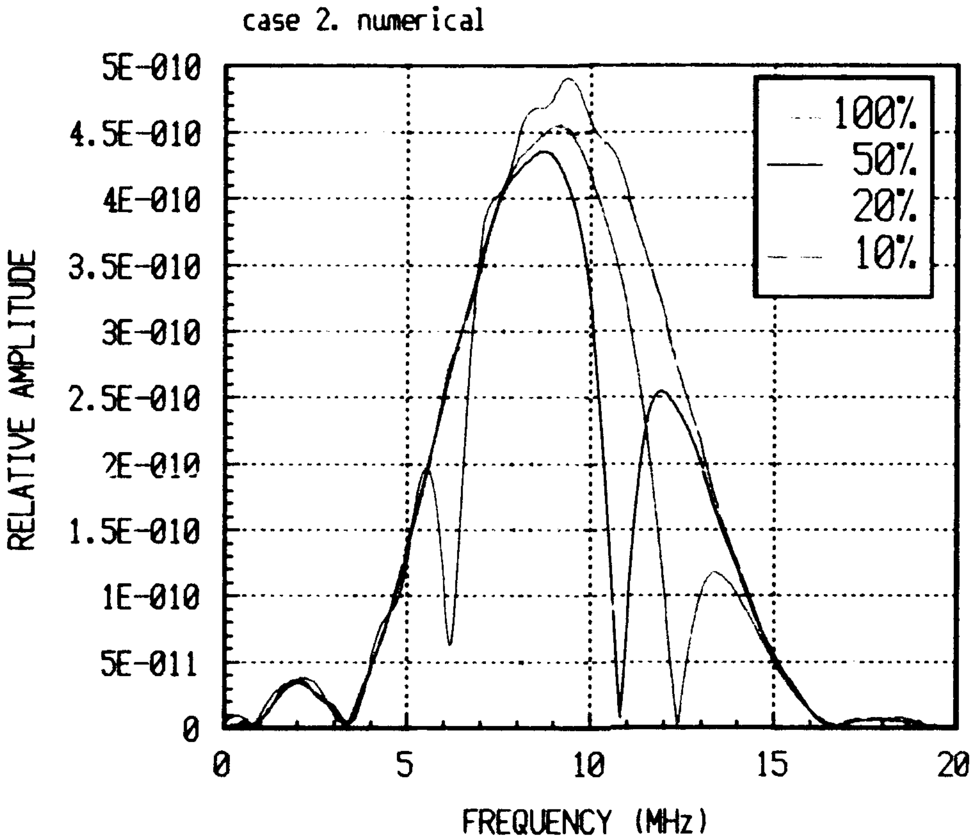


Figure 13. Frequency domain mechanical displacement responses, Case 2, for 10%, 20%, 50%, and 100% bond quality levels

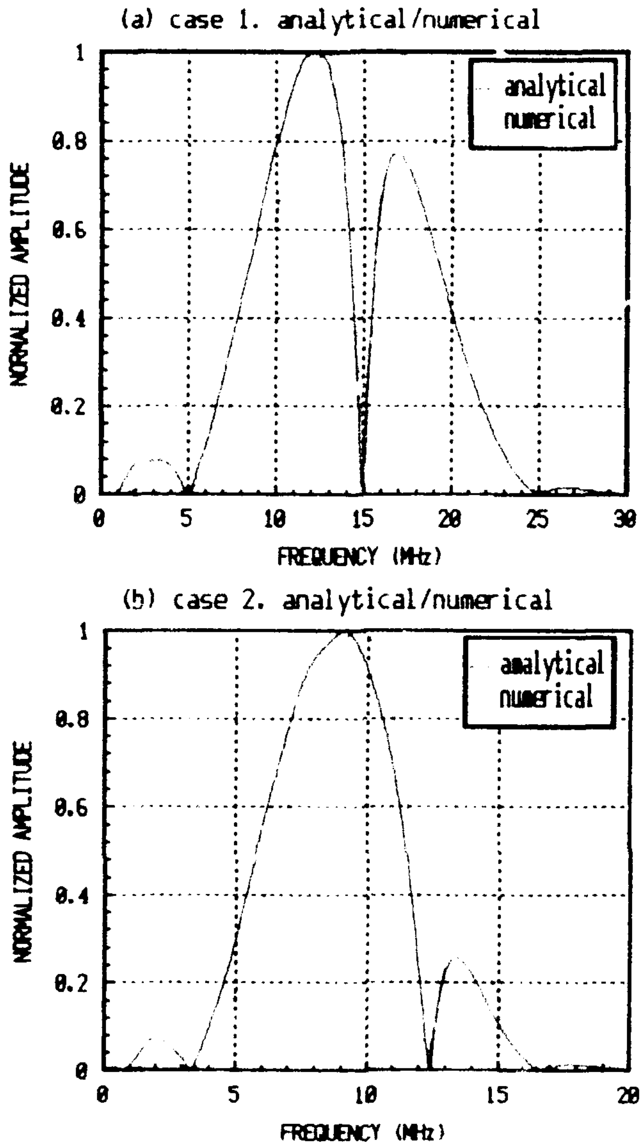


Figure 14. Frequency domain comparisons of analytical versus numerical approaches for good bond (100% bond quality level): (a) Case 1, interfacial layer similar to adherend, and (b) Case 2, interfacial layer similar to adhesive

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ACOUSTIC WAVE PROPAGATION IN AN ADHESIVE BOND MODEL WITH DEGRADING INTERFACIAL LAYERS-
Robert F. Anastasi and Mark J. Roberts

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